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6.5 kW, Yb:YAG Ceramic Thin Disk Laser

William P. Latham, et. al.

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Technical Note

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14. ABSTRACT

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6.5kW, Yb:YAG Ceramic Thin Disk Laser

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Abstract. The operation of a 1030 nm, single, thin disk laser which produced 6.5 kW of laser output power with 57 percent slope efficiency is reported. The Yb:YAG ceramic gain element is 200 μm thick, bonded to a 1 mm, undoped, ceramic YAG cap. The gain element is pumped by diodes at 940 nm. The maximum incident pump intensity was 5 kW/cm^2, which yielded an output intensity of 2.6 kW/cm^2 of multimode laser radiation. Rigrod analysis suggests that the laser operates with inhomogeneous gain saturation. This is attributed to the enhanced, spatial-hole-burning effect when the gain element is adjacent to a mirror. The pump threshold and output intensities were independent of pump spot size, which validates area scaling. Observed thermal lensing contributions include thermal-expansion-induced disk flexure, pump-edge-induced temperature profile and a strong thermal imprint of the cooling nozzle due to the direct jet impingement on the high reflection (HR) coated side. Weak absorption of the 1030 nm intracavity intensity in the undoped cap and/or the anti-reflection (AR) coating led to excess heating that limited the extracted power intensity. These results suggest ceramic Yb:YAG can be scaled to higher powers using optimized thin disk elements and improved disk thermal management techniques.

Introduction

Thin disk laser technology has been around for nearly twenty years. The original idea of the thin disk laser was that the geometry increased the ratio of the surface area to the volume to greatly enhance the ability to cool the thin disk medium. Prof. Giesen‟s group at the Univ. of Stuttgart initially pioneered thin disk laser technology. Since then multiple international programs in thin disk lasers have been created. Usually single crystal Yb:YAG material is used as the active region for thin disk lasers. Single crystal thin disk lasers have been operated at tens of kilowatts. This paper reports the first operation of a ceramic Yb:YAG thin disk laser at the kilowatt power level. The Air Force Research Laboratory/Directed Energy Directorate (AFRL/RD) partnered with the University of Stuttgart, Germany, to establish the hardware for the thin disk laser project at AFRL/RD. The delivered German technology included a 1 cm and 2 cm diameter thin disk mounts with provision for connection to jet impingement thermal management hardware and a diode pump laser mounting system and optical elements. Commercially available thin disk lasers include only 1 cm diameter disks. The German technology utilized capped thin disks. Pump diodes were purchased under separate agreements. The 2 cm diameter testbed has 12.7 KW of diode pump power available for laser testing. In this paper we report on the modification to a thin ceramic disk with an undoped anti-ASE cap[1]. This, in effect, decreases the ASE photon density in the active region which in turn decreases the overall heating.

Thin Disk Characteristics

The thin disk element construction includes an active laser region that consists of a substrate material (usually ytterbium aluminum garnet (YAG) crystal or ceramic) which is doped with ytterbium.

Then, the element may include a heat sink or a cap that is made of undoped YAG material or both of these. In the processing the heat sink and/or cap must be bonded to the active material and the unit is then coated with an antireflection (AR) coating on the top and a high reflection (HR) coating on the bottom. One purpose of our thin disk project is to establish a reliable source of thin disks and to measure the characteristics of thin disks to optimize the thin disk element, the thermal management, and obtain very high efficiency thin disk lasers. Application of the cap may account for stimulated emission in lateral directions noted in previous experimentation. Disks are ceramic. Contractors are producing Yb:YAG (Yttrium Aluminum Garnet) disks of 200μm thickness, doped at 9%. These features are illustrated in Figure 1. In this work, we demonstrate high power scaling of Yb:YAG ceramic TDL and investigate gain saturation, transverse ASE and thermal lensing contributions.

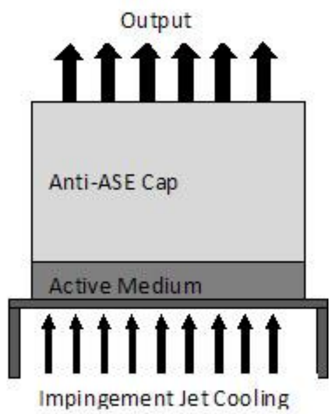
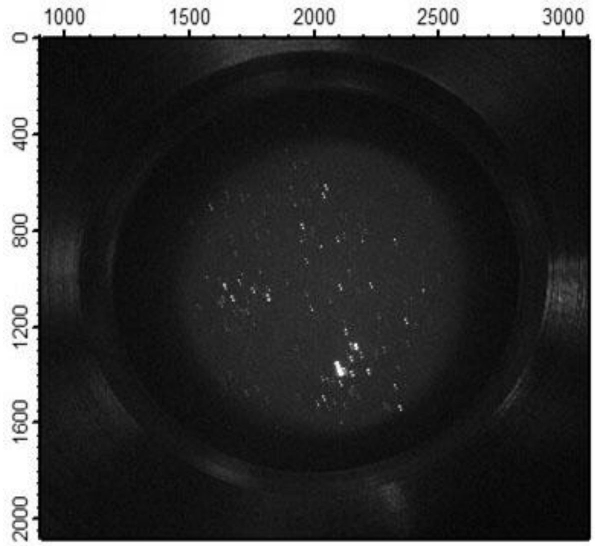


FIGURE 1. Typical thin disk with anti-ASE cap.

Note that Figure 1 is conceptual only. There are many different mounting schemes and many thin disks include heat sink materials behind the active medium layer. One of our first concerns was the bonding of the disks. Figures 2a and 2b show fluorescence images taken with an infrared camera of two different thin disks. Figure 2a has many fewer impurities than the disk shown if Figure 2b. Because of these scattering centers the disk PPK1204, see figure, heats up too much to be useable under lasing conditions. This disk could readily break up under too much heat load into the disk. The second disk shown in Figure 2b, PPKY1205, was used to obtain the maximum measured output power to date. In the manufacturing process the bonding resulted in the formation of scattering centers. At this point the formation and variations is not understood.



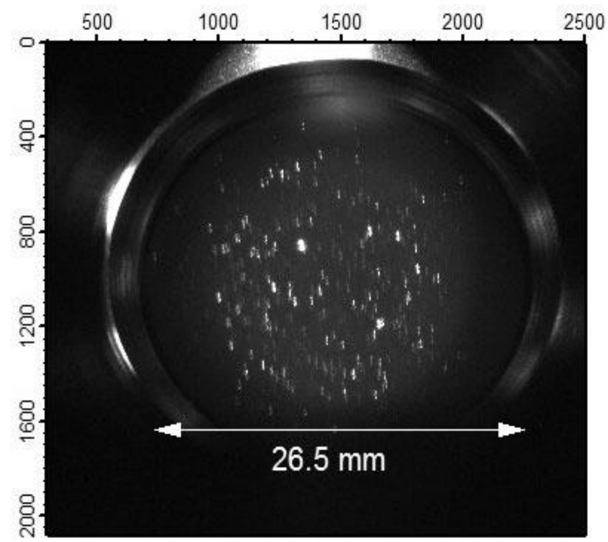


FIGURE 2a, 2b. PPKY1204 and PPKY1205, respectively

High Power Ceramic Thin Disk Laser Experiment

Next we consider the output power and slope efficiency for a single thin disk as shown in Figure 3. The maximum power output for this case was 6.5 KW created by 12. 7 kW of pump power with a slope efficiency of 53 %. Note that the cap heating slope is 30 ^{0}C/kW/cm^2.

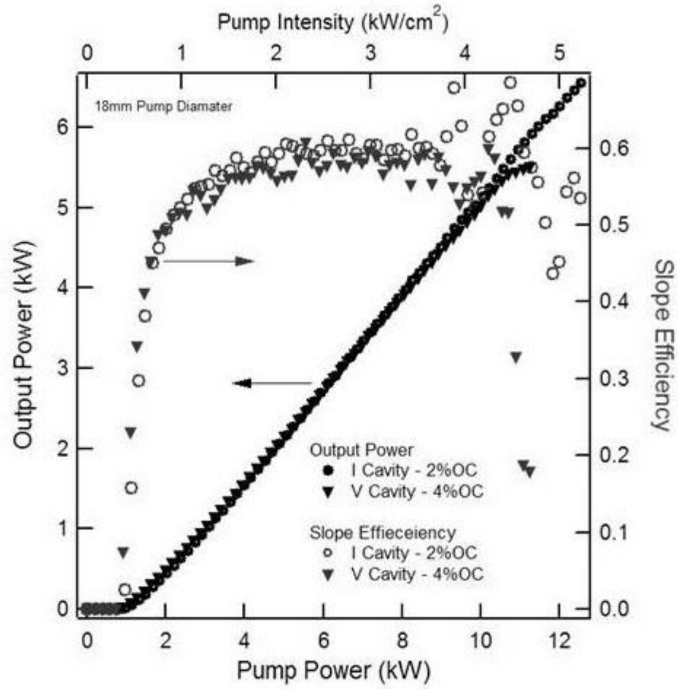


FIGURE 3. Output power for the I and V cavities

The resonator cavity consists of a 2 m radius of curvature (rcc) concave partially transmissive outcoupling mirror and the thin disk gain element at the opposite end of the two element cavity in an I configuration. A „V" cavity consisting of three mirrors was also tested. Here, the thin disk gain element is positioned between a flat mirror and a partially transmissive 2 m radius of curvature concave outcoupling mirror. The three mirrors are arranged in a V configuration. The two cavities I and V are differentiated by the double gain pass at the thin disk in the V cavity. This leads to an increase in the thermal lensing of the incident surface that can force the cavity to go unstable. However, further analysis showed that the thin disk bows outward due to the substantial thermal loading. Taking into account the bowing, Figure 4 shows the cavity stability as a function of the change in the radius of curvature (rcc) of the thin disk. The V optical resonator transitions to an unstable region from a stable one if the bowing is too severe and that this effect shuts off lasing at about a 2m rcc. The shut off occurred at about a power of $4.5 kW/cm^2$.

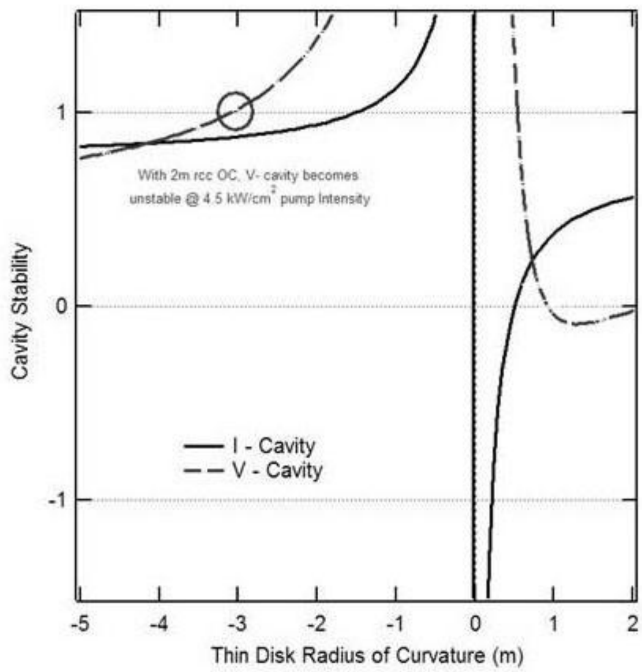


FIGURE 4. Stability plot for I and V cavities.

Figure 5 shows the results of the power output versus outcoupling percentage for both the I cavity and the V cavity. The V cavity has a fold to double the number of passes on the thin disk element. The Rigrod curve is best fit by assuming that the gain medium in inhomogeneous broadened due to spatial hole burning in the gain.

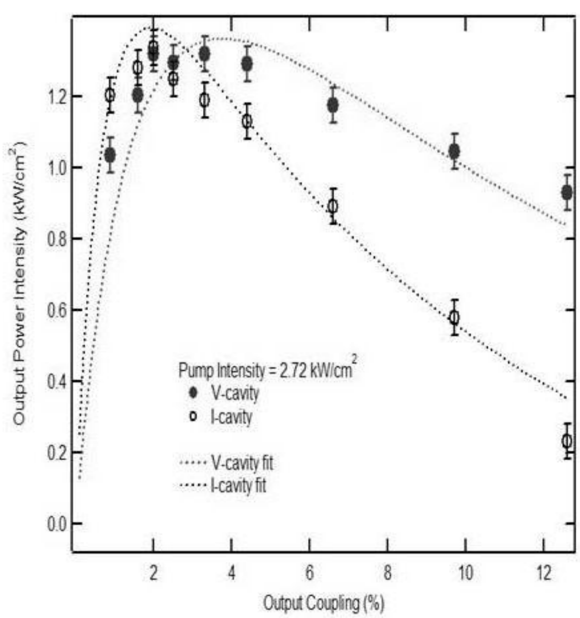


FIGURE 5. Rigrod fit to raw data.

The equations for this fit are given by[2,3,4,5]

$$I_{I,\{V\}}(T_{OC}) = \frac{T_{OC} I_{sat}}{2\{2\}} \left[\left(r_{I,\{V\}}(T_{OC}) \right)^{N} - 1 \right]$$

$$r_{I,\{V\}}(T_{OC}) = \frac{\{2\} LnG}{Ln\left(\frac{1}{1 - T_{OC}} \right) + Loss_{I,\{V\}}}$$

Where T_{OC} is the output coupling transmission, I_{sat} is the saturation intensity, LnG is the roundtrip gain for the I-cavity, r is the pump parameter, $Loss$ is the round trip loss, N=1 (2) for homogeneous (inhomogeneous) saturation. The factor of 2 in the curly bracket is for the V-fold cavity equations where the double pass per round trip results in twice the I-cavity gain and gain saturation at four times the intracavity intensity. The corresponding curve fits are imposed on the experimental data with fitting parameters I_{sat} = 4.6 kW/cm^2, G = 1.26 (small signal gain g_{ss} = 5.8 cm^{-1}), N = 1.99, $Loss_I$ = 0.02, $Loss_V$ =0.042. This fit-extracted gain is consistent with gain measurement of a 1030 nm probe beam for a blocked cavity at lower pump powers. The shift in the gain profile to higher wavelength prevented reliable gain measurement at higher pump powers. The V-fold cavity loss is roughly twice that of the linear cavity. This is consistent with the predominance of the loss being in the disk since the V-fold cavity has twice the number of passes through the disk per round trip. This loss is due to scattering from inclusions and voids in the diffusion layer (observed in fluorescence images of the lasing disk) and absorption in the undoped cap and or the AR coating.

Lastly we discuss the surface temperature profile taken with an IR camera in the 8-14 micron region. The pump beam intensity is well represented by a super-Gaussian in shape with 11mm (dotted curve), and 18 mm (solid curve) diameter. In both cases the pump power is 6.5kW. The temperature profile mimics the input profile with the addition of an annulus type of ASE emission at about 15mm radius.

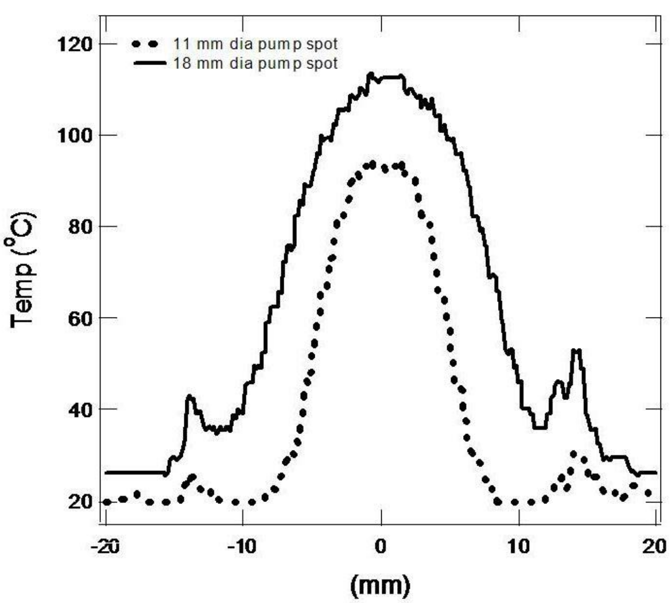


FIGURE 6. Surface temperature profile

We note that the heating of the undoped cap is proportional to the intercavity power, inversely proportional to the output coupling, and suggests deleterious impurity absorption in the cap. Our future plans include a more detailed study of these disks. This will include measuring and modeling the lasing and non-lasing surface temperature profiles along with the curvature of the AR surface as a function of input power. We will also look at the temperature induced optical path in the disk due to both the pump profile and the ASE Additionally some unanswered questions are the scatter, ASE spectral and temperature characteristics and the reabsorbed fluorescence. These are all intimately connected to the energy balance conditions.

Conclusions

We extracted 6.5kW from a single ceramic disk with an anti-ASE undoped cap of the same material as the lasing medium. The bonding is critical and each stack has to be investigated as to scattering impurities that may lead to breakage. This formation of these scattering and absorbing centers in not understood. We have also shown that if too much power is absorbed the cavity can go unstable due primarily to the induced surface curvature. This effect may be over come at cryogenic temperatures or a different cooling scheme. The input pump beam has the shape of a super-Gaussian which is imprinted onto the surface temperature supplemented with a low power ring of ASE. There are several other observations not noted above. Rigrod analysis suggests that the laser operates with inhomogeneous gain saturation. This is attributed to the enhanced spatial-hole-burning effect when the gain element is adjacent to a mirror. This leads to a full modulation of the intracavity intensity at the high reflector side that washes out axially. Reduced gain extraction close to the intensity null regions reduces the effective gain length. Further, the pump threshold and output intensities were independent of pump spot size suggesting that transverse ASE does not clamp the axial gain for up to a pump spot diameter of 18 mm. Observed thermal lensing contributions include: thermal-expansion induced disk flexure, pump-edge-induced temperature profile and a strong thermal imprint of the of the cooling nozzle due to the direct jet impingement on the high reflection (HR) coated side. Weak absorption of the 1030 nm intracavity intensity in the undoped cap and/or the anti-reflection (AR) coating led to excess heating that limited the extracted power intensity.

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